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Research Article

Oropharyngeal articulation of phonemic and phonetic nasalization in Brazilian Portuguese

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ABSTRACT

The phonological feature [±NASAL] does not distinguish systematic oropharyngeal differences between oral, nasal, and phonetically nasalized vowels. A variety of studies now show that oropharyngeal shape may systematically enhance or compensate for the acoustic effects of nasal coupling. Additionally, the phonetic implementation of [−NASAL] vowels in oral and nasal contexts is a matter of some controversy. While the velopharyngeal opening of these vowels has been inferred from aerodynamics, we know of no attempt to directly study the oropharyngeal articulation of underlyingly oral vowels in nasal and oral contexts in a language that may also have phonemically [+NASAL] vowels. In this study, real-time magnetic resonance imaging (rt-MRI) is used to study vocal tract configuration in Brazilian Portuguese (BP), a language that arguably has [+NASAL] (phonemically nasal) vowels and two classes of [−NASAL] vowels (oral and phonetically nasalized). Results show oropharyngeal differences between nasal and oral vowel congeners /a∼ã/, /i∼ĩ/ and /u∼ũ/, which arguably enhance well-known acoustic effects of nasal coupling on vowel height. In addition, nasal coda consonants emerge following nasal vowels. Phonetically nasalized vowels, on the other hand, show no sign of nasal enhancement, including nasal coda emergence, implying they are underlyingly oral vowels, despite the environment in which they occur. We argue that nasal vowels in BP are underlyingly /Ṽ/, rather than /VN/ sequences, the latter distinction being reserved for nasalized vowels. Articulatory divergence of [+NASAL] and [−NASAL] vowels has implications in perception, sound change, and the phonetic implementation of nasality.

1. Introduction

The phonological status of nasal vowels[1] has been of interest for some time, and their underlying representation, particularly in Brazilian Portuguese (BP), is a matter of some debate. One theory posits that nasal vowels are composed of two underlying segments—an oral vowel followed by a nasal segment, which is either specified as a particular lexically-dependent phoneme, or a nasal archiphoneme with a phonetic implementation dependent on the following sound (Almeida, 1976; Cagliari, 1977; Câmara, 1970, 1977; Guimarães & Nevins, 2013; Lipski, 1973; Lipski, 1975; Paradis & Prunet, 2000). According to this theory, which stems from both historical and phonetic accounts, [Ṽ] is the surface form of the vowel, though the underlying form is /VN/ (Mateus & d'Andrade, 2000). Nasal airflow, which indirectly reflects velopharyngeal opening, is gradual in both French and BP nasal vowels (Cohn, 1990; Desmeules-Trudel, 2015). Desmeules-Trudel (2015) interprets this as indicative of an oral vowel followed by a nasal consonant. Cohn (1990, p. 89) also regards such behavior as indicative of phonetic nasalization, particularly in languages with no phonological opposition between oral and nasal (like English). An opposing theory, based on historical and instrumental evidence, claims that nasal vowels are inherently /Ṽ/ in their underlying form, as well as their surface representation (Sampson, 1999; Shosted, 2003). Understanding the underlying form of nasal vowels is important for explaining nasalization itself, and for

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[1] Barbosa and Albano (2004) use the term "nasalized" vowels to describe these vowels. However, we follow the conventions in Stevens (2000) and refer to these as *(phonemic) nasal* vowels, as they are arguably phonemically distinct from oral vowels. Following Cohn (1990), we use the term *(phonetically) nasalized* to refer to oral vowels that undergo nasalization due to proximity to a nasal segment.

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making predictions regarding the evolution of languages with nasal vowels in their inventories.

Recent instrumental advances allow direct comparison of the articulatory configurations of oral/nasal vowel congeners, presumed in previous works to differ only with respect to velopharyngeal opening (see Section 1.1.2). These methodologies provide phonetic evidence directly related to the debate over the phonological status of nasal vowels. If nasal vowels assume systematically different oropharyngeal[2] configurations with respect to their oral congeners, this suggests oral and nasal vowels in BP are produced using a distinct set of purposeful oropharyngeal motor targets and trajectories (a motor plan) that involves more than just oral/nasal coupling. Given that phonological contrast is routinely ascribed to those speech sounds that (a) result in lexical distinctions and (b) manifest systematic phonetic differences, we argue that at least some of the nasal vowels of BP should be regarded as phonemic. As in French—an arguably better-studied language with regard to vowel nasalization—we believe that oropharyngeal differences between oral and nasal vowels must be taken into account in studying BP dialectology and sound change.

The objective of this study is to substantiate the acoustic differences between these vowels that cannot be ascribed to nasal coupling, such as F1 raising for nasal high vowels compared to oral high vowels. We do this through an articulatory comparison of nasal and oral vowel congeners in BP. A further contribution is to explore whether phonetically nasalized vowels assume different articulatory targets with respect to their underlyingly oral and nasal congeners.

1.1. Vowel nasalization

1.1.1. Acoustic effects of nasalization

The description and quantification of nasal acoustics requires significant attention, as the coupling of additional cavities to the oropharyngeal tube adds complexity to the acoustic signal emanating from the vocal tract (Chen, 1975; Fant, 1960; Feng & Castelli, 1996; Fujimura & Lindqvist, 1971; Maeda, 1982a, 1982b; Pruthi & Espy-Wilson, 2007; Stevens, 2000). Nasalization is roughly defined by the lowering of the velum, which results in the opening of the velopharyngeal port, thereby coupling the oropharyngeal and nasal passages. The nasal cavity's larger surface area (due primarily to the tissue covering the scroll-like nasal turbinates), as well as the paranasal sinuses, absorb and reduce energy in some frequency bands. The general effect is to lower amplitudes and increase formant bandwidths in all cases. Additional spectral perturbations are due to the presence of formants and antiformants associated with particular vocal tract geometries. These effects are of particular consequence in the lower frequencies surrounding the first formant (Stevens, 2000). The phonological implications of this effect are well-studied (Beddor, 1983; Beddor & Hawkins, 1990).

The effect of nasalization on F1 can also be cast in terms of the increase in the number of pole-zero pairs in the transfer function (Maeda, 1993; Stevens, 2000), also known as nasal formants and antiformants. Because there are already poles and zeroes in the oropharyngeal transfer function, it is difficult to posit the frequency of the nasal antiformants *a priori*. A spectral comparison of oral and nasal vowel congeners is helpful but this procedure, too, is problematic. It assumes identical oropharyngeal configurations (aside from velopharyngeal opening) for the contrastive vowels. This assumption is now well-known to be misleading (see Section 1.1.2).

Many measures have been posited to quantify the acoustic effects of nasality (e.g., $A1, A1-P0, A1-P1$, Center of Gravity below $1000Hz$, where $A1$ is the amplitude of the first formant, $P0$ is the amplitude of the first nasal formant, and $P1$ is the amplitude of the second nasal formant (Berger, 2007; Chen, 1997; Glass & Zue, 1985; Pruthi & Espy-Wilson, 2007; Styler, 2017)). Styler (2017) shows that $A1-P0$, F1 bandwidth, and spectral tilt are the most robust measures for definitively distinguishing oral/nasal congeners in French.

The coupling of oral and nasal cavities systematically affects the frequency domain of the lower formants. Fujimura and Lindqvist (1971, p. 552) claim that all formants of nasalized vowels "shift monotonically upwards." When velopharyngeal opening is large enough to create a high-amplitude nasal formant, the formant values of low vowels decrease (Diehl, Kluender, Walsh, & Parker, 1991). The opening of the velopharyngeal port shifts the expected resonances of the oral cavity (relative to comparable vowels with a closed velopharyngeal port), due to the overall change in tract configuration. For non-low vowels, the nasal formant occurs in a frequency range above that of F1, thereby spreading the distribution of energy upwards. For the low vowels that already exhibit a high F1, the nasal formant occurs below F1, thereby spreading energy lower compared to its oral congener. Thus, nasal vowels are often considered to be centralized along the height axis (Beddor, 1993). Serrurier and Badin (2008) also claim that F2 of front vowels is lowered as an effect of nasalization. This has been confirmed elsewhere (Feng & Castelli, 1996; Carignan, 2013), and is possibly due to velic lowering itself (Shosted, Carignan, & Rong, 2012).

1.1.2. Articulatory enhancement and nasalization

Phonemic nasal vowels are considered distinct from oral vowels in the vowel inventory of a language because they differentiate minimal pairs. For example, the French words /pɛ/ *paix* 'peace' and /pɛ̃/ *pain* 'bread' nominally differ only in the nasal quality of the vowel. Some previous studies of nasalization compare phonemic oral and nasal vowel pairs assuming that the only physical difference between the two is the positioning of the velum; that is, a nasal vowel is produced by opening the velopharyngeal port and maintaining the oropharyngeal configuration associated with the oral vowel (Berger, 2007; Feng & Castelli, 1996; Jacques, 2014; Maeda, 1982b; Narang & Becker, 1971; Pruthi, 2007; Pruthi, Espy-Wilson, & Story, 2007). However, other studies, including articulatory analyses, suggest that the position of the tongue, lips, and pharynx, as well as the velum, may differ between oral and nasal vowel congeners, discussed below.

The oropharyngeal articulation of French phonemic nasal/oral vowel congeners has been thoroughly studied—these vowels display differences in tongue height, labial aperture, pharyngeal constriction (Bothorel, Simon, Wioland, & Zerling, 1986; Brichler-Labaeye, 1970; Carignan, 2013; Carignan,

[2] Throughout this paper, we use the term oropharyngeal to refer to non-velopharyngeal articulations.

2014; Carignan, Shosted, Fu, Liang, & Sutton, 2015; Delvaux, Metens, & Soquet, 2002; Engwall, Delvaux, & Metens, 2006; Montagu, 2007; Zerling, 1984), as well as phonation type (Carignan, 2017). European Portuguese shows subtle articulatory distinctions for [ɐ̃] and [õ] in comparison to their oral congeners, more so than in other oral/nasal vowel pairs (Martins, Oliveira, Silva, & Teixeira, 2012; Oliveira, Martins, Silva, & Teixeira, 2012; Teixeira et al., 2012). Hindi oral and nasal vowels also display distinctions in their articulations—"the tongue body is generally lowered for back vowels, fronted for low vowels, and raised for front vowels (with respect to their oral congeners)" (Shosted et al., 2012, p. 455). Articulatory differences between oral and nasal vowels in BP have also been demonstrated in the oral cavity and pharynx (Barlaz, Fu, & Dubin, et al., 2015a; da Matta Machado, 1993; Shosted et al., 2012; Shosted et al., 2015; Shosted, 2015). Breathiness interacts with nasalization in Southern Yi (Garellek, Ritchart, & Kuang, 2016), indicating that changes in phonation may be associated with nasalization, in addition to oropharyngeal adjustments. Conversely, articulatory adjustments may compensate for the acoustic effect of oral-nasal coupling in languages that do not maintain phonemic nasal vowels, such as American English (Arai, 2004; Carignan, Shosted, Shih, & Rong, 2011).

Maeda (1990) argues that multiple configurations of the vocal tract may be employed to produce the same phonemic vowel, though the many articulatory degrees of freedom can be constrained by covariation in position (Lindblom, 1990). Some of these gestures produce similar acoustic outputs. While these features can be considered redundant (Stevens, Keyser, & Kawasaki, 1986), the articulatory gestures can be considered conducive to, if not necessary for, enhancing an acoustic output (Barlaz, Fu, & Dubin, et al., 2015a; Carignan, 2013; Carignan, 2014; Diehl et al., 1991; Kingston & Diehl, 1994; Perkell et al., 1997; Stevens & Keyser, 2010). Based on this argument, oropharyngeal articulations can be considered conducive to increasing the perceptual impact of the acoustic effects of velopharyngeal opening on nasal vowels (e.g., in French (Carignan, 2013)). Conversely, articulatory strategies in the oral cavity can be used to counteract the acoustic effect of oral-nasal coupling, presumably to maintain phonemic category stability (Carignan et al., 2011). These redundant oropharyngeal articulations can be considered parts of the motor plans for these sounds (Stevens et al., 1986), i.e., the various articulatory movements that can achieve the same acoustic goal, also known as motor equivalence (Hughes & Abbs, 1976).

Phonemic nasal/oral vowel congeners result in lexical differences. Phonetic nasalization occurs when a vowel adjoins a nasal segment (often a consonant), and becomes nasalized due to velopharyngeal coarticulation with that sound. For example, the American English word /ɹæn/ *ran* is produced with a heavily nasalized vowel as [ɹæ̃n], though this surface-nasalized vowel is not considered a separate phoneme from the vowel in the word *rat*. This suggests that the oral vowel ought to be recoverable by simply eliminating the coarticulated velopharyngeal gesture. While phonemic nasal vowels and phonetically nasalized vowels are both described in regards to oral/nasal coupling, their phonological status and phonetic implementation are different. According to Cohn (1990), phonemic nasal vowels are considered [+NASAL], whereas phonetically nasalized vowels are [−NASAL]—i.e., oral—in their featural specifications.

Only a limited amount of work considers how phonemic and phonetic nasalization are realized phonetically in a single language. Airflow evidence (Cohn, 1990) suggests phonetic and phonemic nasalization are associated with different patterns of velopharyngeal control. Articulatory differences can be used to argue for one proposal or another, as in Sundanese. Nasal airflow profiles brought Cohn (1990) to the conclusion that nasal vowels are phonemic in this language. Meireles, Goldstein, Blaylock, and Narayanan (2015) shows differences in gestural timing, and Desmeules-Trudel (2015) shows differences in airflow profiles in nasal and nasalized vowels in BP. A study of the articulatory differences in phonemically nasal and phonetically nasalized vowels may help to unpack the phonetic content of the phonological feature [NASAL] and better assess its utility in phonological models.

Moreover, oropharyngeal articulatory adjustments may arguably lead to enhancement or attenuation of the acoustic consequences of phonemic and phonetic nasalization, respectively. Enhancement may act to preserve a phonemic contrast, while attenuation may act to maintain categorical stability. Examining a language that maintains both phonemic and phonetic nasalization can help us understand the complex interaction between enhancement and attenuation, and their role in phonetic implementation of phonological contrast. This can also provide insight into the amount of phonetic variability allowed within a phonological category.

1.2. Nasal vowels in Brazilian Portuguese

The phonemic inventory of BP includes seven phonemic oral vowels in stressed position /i e ɛ a ɔ o u/ (e.g., *suco* /ˈsukʊ/ 'juice') and five phonemic nasal vowels, also in stressed position /ĩ ẽ ɐ̃ õ ũ/ (e.g., *sunto* /sũtʊ/ 'summed up') (Barbosa & Albano, 2004). In pre-stressed position, there are five oral vowels and five nasal vowels: /i e a o u ĩ ẽ ɐ̃ õ ũ/. Barbosa and Albano (2004) claim that both nasal and nasalized vowels can occur in pre-stressed position. In post-stressed position, a four-oral vowel contrast exists /ɪ ɐ ʊ ë/ (e.g., *saco* /sakʊ/ 'bag'), and the five phonemic nasal vowels are preserved (Barbosa & Albano, 2004).

BP nasal vowels and their oral congeners have been shown to manifest distinctive oropharyngeal configurations using cineradiographic data (da Matta Machado, 1993), electromagnetic articulography (Shosted et al., 2015; Shosted, 2015; Shosted et al., 2016), and real-time magnetic resonance imaging (rt-MRI) (Barlaz, Fu, & Dubin, et al., 2015a). Specifically, front oral vowels /i/ and /e/ are more fronted than their nasal congeners /ĩ/ and /ẽ/, showing similar trends to those observed in French. With regard to the low vowels, /a/ is considerably more open than its nasal congener. Barlaz, Fu, and Dubin, et al. (2015a) also shows fronting of the tongue blade for /ũ/ in comparison to /u/. Nasal coda consonants are reportedly emerging in BP following non-low nasal vowels (Barlaz, Fu, & Shosted, et al., 2015b; Shosted, 2003; Shosted, 2006; Shosted, 2011), perhaps as another strategy to maintain or enhance the phonemic oral/nasal vowel distinction. For example, articulatory results (Barlaz, Fu, & Shosted, et al., 2015b; Shosted, 2011) show the vowel /ũ/ (such as in the word *bebum*

/bebũ/ 'bad smell') being produced as /ũŋ/ ([bebũŋ]), and the vowel /ĩ/ (as in *capim* /kapĩ/ 'species of grass') being produced as /ĩɲ/ ([kapĩɲ]).

BP oral vowels undergo phonetic nasalization when adjacent to a nasal segment. Some scholars posit that the distinction between the two nasal vowels is due simply to syllable structure. Phonemic nasal vowels appear before a tautosyllabic nasal consonant, as in *campo* [kam̥.pu] 'field', whereas phonetically nasalized vowels appear before a heterosyllabic nasal consonant, as in *cama* [kã.ma] 'bed' (Desmeules-Trudel, 2015; Barbosa & Albano, 2004). Phonetic differences have been reported between phonetically and phonemically nasal vowels. Nasal vowels demonstrate a relatively smaller $A1-P0$ value than nasalized vowels, which implies a larger velopharyngeal opening for the nasal vowels (Marques, 2014). Differences in gestural timing have also been noted between underlying nasal vowels and oral vowels that undergo progressive nasal assimilation, with nasal vowels displaying full oral and nasal gesture synchrony (Meireles et al., 2015). Finally, there is evidence of aerodynamic and durational differences, as well. Nasal vowels show longer durations, which is arguably another phonetic difference that separates oral and nasal vowel phonemes (de Medeiros, 2011).

1.3. The current study

The current study expands previous research on BP nasal/oral vowel congeners through use of rt-MRI. The goal of this study is a comprehensive examination of the articulation of BP vowels using images of the entire oropharyngeal tract, in order to determine the articulators responsible for articulatory differences across time. Comparisons between phonemic nasal and phonetically nasalized vowels will provide insight into the articulatory strategies used for enhancement and attenuation, and will determine how distinctive or stable these strategies are within a single linguistic system. This study will shed more light on the phonological status of nasal vowels in BP, by comparing the oropharyngeal articulations of oral/nasal vowel congeners and determining whether these congeners maintain the same configurations in the oropharyngeal tract (excluding velopharyngeal opening, of course). We are including surface-nasalized vowels (those that are uncontroversial sequences of oral vowel plus nasal consonant) in order to tease apart the relationship between the nasal and oral vowels. Specifically, if nasal vowels pattern with nasalized vowels, then nasal vowels may be adequately characterized as /VN/ sequences. Otherwise, it seems justifiable to consider nasal vowels as unitary elements, based on articulatory and acoustic evidence.

2. Material and methods

2.1. Speakers

Twelve speakers of BP—seven males and five females—were recorded. Both male and female speakers were recruited. It is important to note that very few studies involve gender as a variable in the study of nasalization, so little is known in this regard. One study has shown that articulatory modifications differ based on gender (Engwall et al., 2006). This was arguably to compensate for differences in anatomy: speakers with smaller nasal cavities, often women, manifest weaker effects of nasalization, and therefore would arguably require less articulatory compensation in the case of phonetic nasalization, or more enhancement strategies for phonemic nasalization. Delvaux et al. (2002) shows differences in nasalization, specifically in tongue position, for male and female speakers. We include both males and females to determine if any gender differences exist, as women are considered more likely to use innovative forms in sound change (Labov, 2001).

All speakers were from the states of São Paulo (4 males, 2 females) and Minas Gerais (3 males, 3 females), in southeastern Brazil, and ranged in age from 21 to 43 (median = 30) years old. No speakers reported having speech or hearing problems.

2.2. Materials

Twelve target words were chosen for this experiment. Productions of /a/, /i/, and /u/ were compared to their nasalized and nasal congeners. Two nasal vowels—in word-medial and word-final position—were included to determine any positional or morphophonological effects on nasalization, as previous research have used these two different types of stimuli (Barlaz, Fu, & Dubin, et al., 2015a; Desmeules-Trudel, 2015; Shosted et al., 2015). Due to the inherent need for the nasalized vowels to occur in a [C_.N] environment (see Section 1.2 for the syllabic properties of nasalization), trisyllabic words were chosen, with the second syllable containing the target vowel under primary word stress. For the word-final nasal vowels, disyllabic words were chosen, with the second syllable containing the (stressed) target vowel. To control for coarticulatory effects, the word list was constructed so that all target vowels occurred between a labial and alveolar consonant. The wordlist was also balanced for frequency effects across three corpora of Brazilian Portuguese (Davies, 2016; Linguateca, 2016; Cristófaro-Silva, de Almeida, & Fraga, 2005). The full word list is provided in Table A.4. Target words appeared in the carrier phrase *digo X duas vezes* [dʒigu X duaz vɛzɨs] 'I say X two times'. The syllable containing the target sound received phrasal prominence as well as primary word stress.

2.3. MRI acquisition and vocal tract aperture extraction

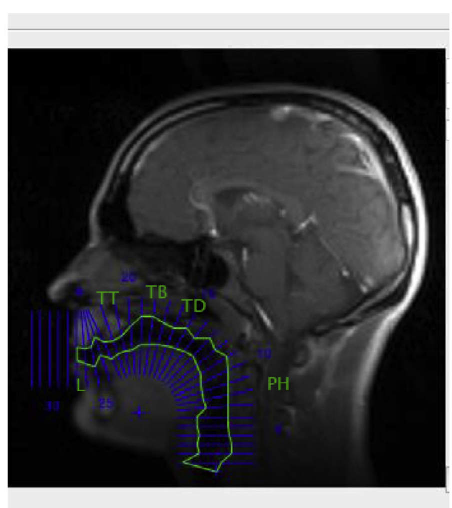
rt-MR images were obtained using the Partial Separability model (Fu et al., 2012; Fu et al., 2015; Liang, 2007). This allows for a nominal frame-rate of 100 frames per second in a single slice scan, taken in a mid-sagittal orientation. Spatial coverage for the slice is 128×128 voxels, with each voxel measuring $2.2 \times 2.2 \times 6.5$ (through-plane depth) mm^3. Participants lay supine in a 3 T Siemens Trio MRI scanner at the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign. Participants' heads were secured in place with a head coil that limited head movement, and further stabilized with foam pads. The participants wore an MR-compatible optical microphone (Dual Channel-FOMRI; Optoacoustics, Or Yehuda, Israel). The microphone's noise-attenuating software was used to reduce the scanner's background noise. This noise-reduced signal was used for manual segmentation of target vowels in Praat (Boersma & Weenink, 2012). The target words in the carrier phrase were presented to the subjects in randomized order as text via a MR-safe projector. Participants were instructed to repeat the full phrase at their normal speaking rate until the scanner noise ceased. Each scan took 89 s. The twelve scans took a total of 17.8 min per participant. Because of variation in speaking rate across speakers, an unequal number of repetitions of each vowel was recorded, ranging from 23 to 48 repetitions per vowel, across speakers. Speakers produced comparable numbers of each target word in their individual recording sessions.

The vocal tract aperture function was calculated by superimposing a semi-polar grid on a random MR image extracted from the vowel, based on manually-selected anatomical landmarks using a GUI in MATLAB (Narayanan et al., 2014). This grid originated at the glottis and ended at the lips, and was applied to all midsagittal images within the vowels' segmentation boundaries (Fig. 1). Cross-dimensional boundaries of the vocal tract were determined by seeking maximal pixel intensity differences along each grid line from the glottis to the lips. The distances between these lower and upper bounds were used to calculate the aperture of the vocal tract along each grid line. This resulted in a function of vocal tract aperture (AF) by distance from the glottis (AFx), both given in millimeters.

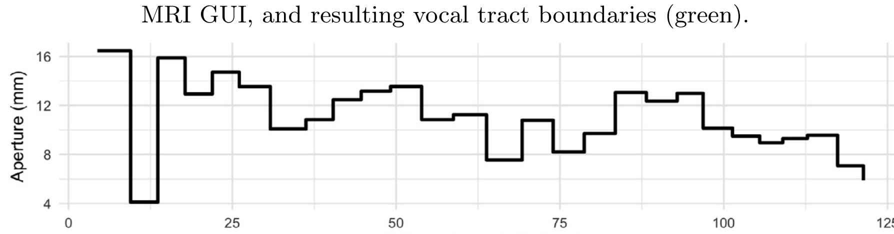
Tongue shape was analyzed in order to further understand the articulatory mechanisms associated with nasalization in different contexts, and to further understand which articulators were responsible for changes in AF (critically, whether the velum or tongue dorsum was responsible for changes in this particular region of the vocal tract). Using the same GUI in MATLAB, tongue shape data was collected using the contour corresponding to the inferior edge of the vocal tract (used in calculating AF). While the AF information contains the entire vocal apparatus, the gridlines associated with the glottis, epiglottis, teeth and lips were excluded from the tongue shape analysis.

2.4. Acoustic data collection

To determine whether the articulatory differences in nasality had an effect on acoustic output, high-fidelity acoustic data was recorded. The same speakers who participated in the articulatory study were recorded in a sound-attenuating booth. Speakers wore a C520 head-set microphone (AKG Harman, Stamford, CT) and acoustics were recorded into a PMD570 Solid State Recorder (Marantz Professional, Cumberland, RI) with a Grace m101 preamplifier (Grace Designs, Lyons, CO). The speakers were instructed to lie down on a cot, and to remain as still as possible to mimic the imaging acquisition protocol. Subjects were instructed to repeat the same carrier phrase with embedded target words on the screen for 1.5 min at a normal pace and with neutral intonation. Acoustic data were annotated manually in Praat (Boersma & Weenink, 2012), and twenty values of the first formant were taken in time-normalized intervals from the vowel's duration using FormantPro (Yi, 2007–2015).



(a) Semi-polar grid (blue) on the vocal tract, from the rt-MRI GUI, and resulting vocal tract boundaries (green).



(b) Aperture function of the vocal tract.

Fig. 1. Examples of the outputs of the rt-MRI GUI.

2.5. Statistical methods

A generalized additive model (GAM) was fit to the AF data using the *mgcv* package (Wood & Wood, 2017) in R (R Core Team, 2016) to determine the effect of different conditions on AF values, as a function of AFx. GAM is a generalized linear model, in which the dependent variable depends on smooth functions based on the predictor variables (Wood, 2006). This method is emerging as a way to model dynamic differences in multidimensional linguistic data (Wieling, 2018). GAM was chosen over traditional linear regressions to better capture the complex shape of vocal tract aperture over time. This model served to determine whether there were significant differences in AF as a function of time. The model was compared against traditional linear models, in order to determine the model that best fit the data. Ten (AFx, AF) pairs were taken at normalized intervals throughout the vowels' relative durations. The model includes vowel identity (/a, i, u/) nasality condition (oral, nasalized, word-medial nasal, word-final nasal), speaker, gender, repetition number, and proportion of vowel duration (range 0–1).

To determine the articulators responsible for the most variance between vowel categories and nasality conditions, the AF data for the middle image was included in a principal components analysis (PCA). A separate PCA was conducted for each speaker, due to individual differences in vocal tract anatomy. Each PC was interpreted in articulatory terms, based on the strength of correlation between the gridlines and each PC loading, at a threshold of 0.25 (absolute value). We considered a PC interpretable as a distinct articulatory region if there was at least one set of two or more adjacent gridlines that met the aforementioned correlation requirements.

The articulatory regions that showed the highest degree of correlation with a given PC were extracted for a time-dynamic analysis. Specifically, data from the appropriate gridlines were taken throughout the vowels' relative durations, and integrated into an area value (AV) for each image, determined by calculating the trapezoidal area beneath each gridline. Trapezoidal area was calculated using the aperture at that gridline and the one before as the two trapezoidal bases, and the Euclidean distance between the two gridlines was considered the height of the trapezoid. AV was compared between nasality condition for each vowel using smoothing spline ANOVA (SSANOVA), using the *gss* (Gu, 2007) package. SSANOVA was visualized with the *ggplot2* (Wickham, 2009) package. Bayesian 95% confidence intervals were plotted along the splines—if the confidence intervals did not overlap for a given combination of nasality conditions, they were considered significantly different.

Tongue shapes were calculated for the beginning, middle, and end of each vowel repetition's normalized duration. Tongue shape was plotted using a GAM smooth in the function *ggplot* from the *ggplot2* package (Wickham, 2009)—see, e.g., Fig. 7. Similar to SSANOVA, the GAM smooth shows 95% confidence intervals around the contour. The superior side of the vocal tract was plotted for a randomly-selected vowel repetition using *ggplot2*. This was done to show the relative locations of the passive articulators and the velum, to ensure that any changes in vocal tract area were due to differences in lingual position.

A GAM was fit to the acoustic data to determine the effect of different conditions on F1, as a function of time. The twenty F1 points were used as the dependent variable. The model includes vowel identity (/a, i, u/) nasality condition (oral, nasalized, word-medial nasal, word-final nasal), speaker, gender, repetition number, and proportion of vowel duration (range 0–1, in 20 steps) as predictors. To visualize the differences within vowel category, F1 was compared between nasality condition using SSANOVA. Data was visualized by speaker to account for any individual differences.

3. Results

3.1. Articulatory GAM

The GAM run on the entire AF dataset accounted for 62.3% of the deviance in the data[3]. Vowel, nasality condition, and gender (males showing overall higher AF compared to females, due to having larger vocal tracts) were all significant effects on AF. Directionality of differences for vowel and nasality conditions differed between conditions based on position in the vocal tract. Speaker also showed a significant effect on AF, indicating that individual differences were present in the data. There was no significant effect of time (i.e., proportion of vowel duration) on AF. While this could be interpreted as a lack of significance of the temporal differences between vowels (all of the vowels in question are uncontroversially described as monophthongs), it is also possible that these differences are small compared to distinctions between vowel and nasality conditions. Results of the GAM are summarized in Table 1. The s(X) notation is used to denote a smooth of a continuous predictor variable in the GAM. The intercept is interpreted similarly to that of a linear model with categorical predictors. Here, the intercept represents the nasal /ã/ for female speakers. Estimated degrees of freedom (EDF) and reference degrees of freedom (in parentheses) are given for smooth terms in the model to show effects of time and AFx on categorical conditions.

3.2. PCA-guided analysis

Results of the PCA-guided analysis showed that the first five PCs accounted for 80% or more of the variance in each speaker's AF data. However, only the first three PCs (accounting for an average of 67% of variance, range 54–73%) were interpretable as distinct articulators for each speaker, given the criteria described in Section 2.5. PC1 accounted for an average of 35% of the variance in the AF data for each speaker (range 25–44%). To determine the articulatory meaning of PC1, a graphic comparison of the oral vowels /a/, /i/ and /u/ was prepared for each speaker, as their articulatory settings are maximally distinct. Fig. 2 shows the AF of representative oral vowels in relation to PC1 for speaker BP06.

PC1, which accounted for the highest amount of variance in the data, was explained by the hyperpharyngeal and tongue blade regions for all speakers. In the present study, the hyperpharyngeal region is defined as the top third of the pharynx, up to—but not including—the inferior surface of the velum. The tongue blade is defined as the middle third of the region

[3] This was compared to a linear model, which had an adjusted R^2 of 0.20, and a 5th-order polynomial regression, which had an adjusted R^2 of 0.3066.

Table 1
Results of the GAM for all AF data, including the EDF and reference degrees of freedom (in parentheses) for smoothed model components.

	AF
(Intercept)	−208.84 (9.88)***
Vowel (i)	−0.43 (0.01)***
Vowel (u)	−0.10 (0.01)***
Nasality (nasal_final)	0.04 (0.01)***
Nasality (nasalized)	0.11 (0.01)***
Nasality (oral)	0.28 (0.01)***
Sex (M)	−47.12 (11.65)***
EDF: s(AFx)	0.48 (0.48)***
EDF: s(AFx):Vowel (a)	8.72 (8.72)***
EDF: s(AFx):Vowel (i)	8.72 (8.72)***
EDF: s(AFx):Vowel (u)	8.72 (8.72)***
EDF: s(AFx):Sex (F)	8.61 (8.62)***
EDF: s(AFx):Sex(M)	0.62 (0.62)***
EDF: s(AFx):Nasality (nasal)	4.66 (4.75)***
EDF: s(AFx):Nasality (nasal_final)	8.24 (8.28)***
EDF: s(AFx):Nasality (nasalized)	8.11 (8.17)***
EDF: s(AFx):Nasality (oral)	5.81 (5.91)***
EDF: s(Speaker)	4.99 (10.00)***
EDF: s(Time)	1.00 (1.00)
EDF: s(Speaker,AFx)	100.98 (106.00)
EDF: s(Sex)	0.00 (2.00)***
EDF: s(Sex,AFx)	0.00 (18.00)***
AIC	6449788.13
BIC	6451936.86
Log Likelihood	−3224716.40
Deviance	10180678.66
Deviance explained	0.62
Dispersion	7.70
R^2	0.62
GCV score	7.70
Num. obs.	1321768
Num. smooth terms	15

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

between the tongue tip and the back of the tongue, corresponding to the inferior surface of the velum. One speaker (BP04) only showed PC1 correlation with the hyperpharyngeal region, and another (BP20) showed PC1 correlation with the tongue blade and PC2 correlation with the hyperpharyngeal region. All other speakers showed PC1 correlation with the tongue blade and hyperpharynx simultaneously. Full results of the PC correlates are provided in Appendix B.

As seen in Figs. 2 and 3, PC1 simultaneously shows a strong positive correlation with aperture of the hyperpharyngeal region and a strong negative correlation with aperture of the tongue blade region for speaker BP06. Therefore, as PC1 increases, the tongue blade region becomes more constricted (i.e., lower AF) and the hyperpharyngeal region becomes less constricted (i.e., high AF). Therefore, a higher PC1 for the oral high vowels (/u/ and /i/) is expected, with /i/ expected to have a higher PC1 score due to a more constricted oral cavity. A lower PC1 for the low oral vowel (/a/) is expected. Any differences between oral/nasal congeners can be similarly interpreted. This pattern is seen in Fig. 4, which displays PC1–3 for oral vowels by vowel quality—/a/ manifests the lowest PC1 scores, while /i/ manifests the highest PC1 scores, and /u/ manifests high PC1 scores, though not as high as those of /i/. Differences in AV by vowel category for the hyperpharyngeal and tongue blade positions are discussed below. Note that the discussion of nasal vowels includes both word-medial and word-final nasal vowels.

Results for tongue blade AV for speaker BP06 are provided in Fig. 5. Clear patterns in AV are observed for the vowel category /a/. For all speakers, the oral vowel displays higher AV across time than the nasal vowels, indicating a lower tongue blade position. Tongue blade raising of /a/ due to nasalization

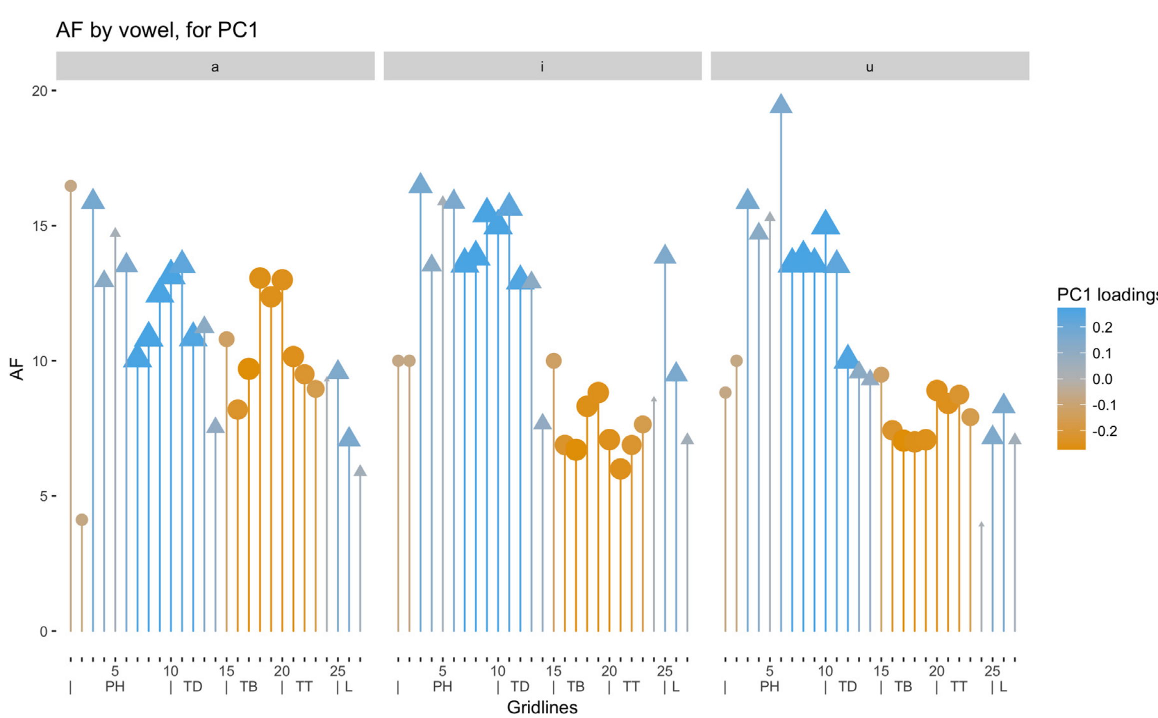


Fig. 2. AF for randomly-selected repetitions of oral vowels and the correlation between each gridline and PC1 loadings, for speaker BP06. Height of each line indicates aperture at that location in the vocal tract, in millimeters. Blue lines and triangular points indicate a positive correlation. Orange lines and circular points indicate a negative correlation. Darker colors and larger point size simultaneously show a relatively stronger correlation. x-axis indicates regions of the vocal tract: PH = pharynx, TD = tongue dorsum; TB = tongue blade; TT = tongue tip; L = lips.

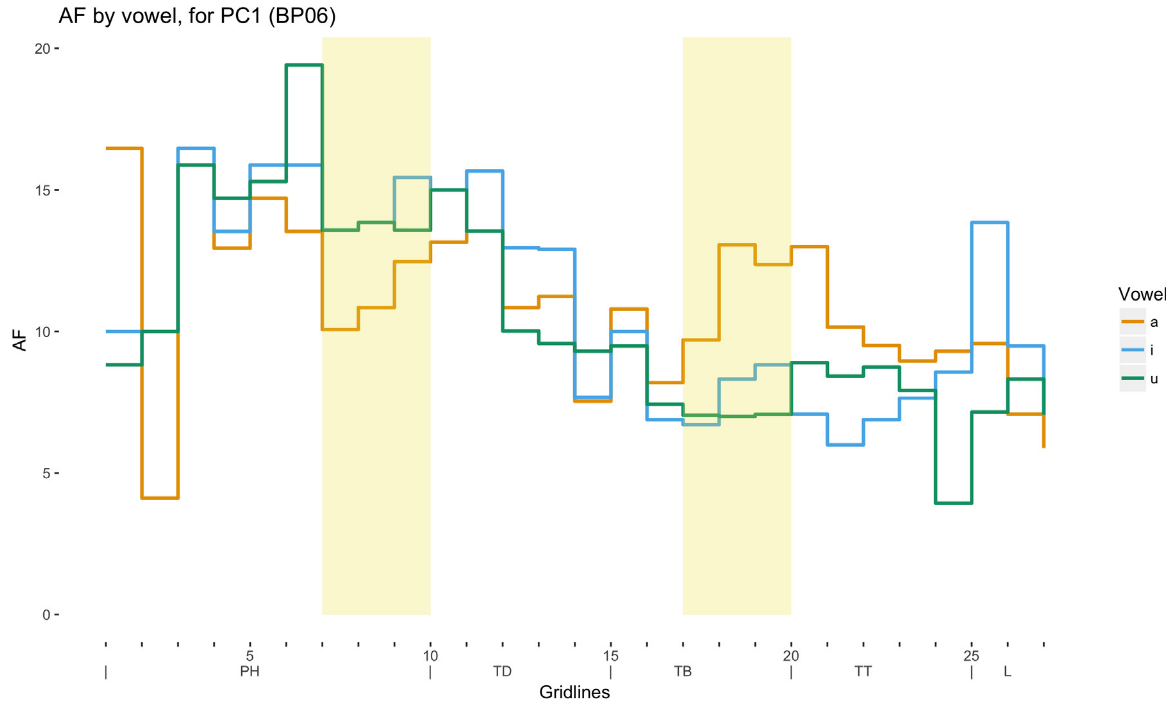


Fig. 3. AF for the same randomly-selected repetitions of oral vowels as seen in Fig. 2, for speaker BP06. Highlighted regions are the articulatory correlates of PC1, based on the relatively stronger correlations between PC1 loadings and appropriate gridlines.

is a well-attested phenomenon in BP, and the nasal vowel is often transcribed as /ɐ̃/ (Shosted, 2015). For the nasalized vowels, two speakers display slightly higher AV (indicating a lower tongue blade position) and one speaker shows similar AV (i.e., overlapping confidence intervals, indicating lack of statistical significance) compared to the oral vowels. Nine speakers produce nasalized vowels with an intermediate tongue blade position compared to the oral and nasal vowels. These speakers also produce the word-final nasal vowel with a slightly lower AV (i.e., higher tongue blade position) compared to the word-medial nasal.

For /i/, the nasal vowels display a wider AV compared to the oral vowels for seven speakers and a similar AV for one speaker. The remaining three speakers display a higher AV for the oral vowels. The contextually nasalized vowel shows a lower AV than the oral vowel, indicating a narrower constriction in the tongue blade region, for five speakers. Two speakers demonstrate a lower AV for the oral vowel, and the remaining four speakers demonstrate similar AV for the oral and nasalized vowels. In regards to the two nasal vowels, the word-final nasal displays a lower AV for six speakers, higher AV for three speakers, and overlapping AV for two speakers, compared to the word-medial nasal, though these differences were comparatively smaller than those between the oral and nasal vowels.

For /u/, the nasal vowels show a higher AV than the oral vowel, indicating a lower tongue blade position, for nine of the eleven speakers for whom tongue blade was an important articulator. The nasalized vowel displays a higher AV than the oral vowel for six speakers, overlapping AV for one speaker, and lower AV for four speakers. The word-medial nasal vowel shows a slightly higher AV compared to the word-final nasal vowels for seven speakers, and lower contour for three speakers. One speaker displays overlapping AV for the two nasal vowels.

Results for hyperpharyngeal AV for speaker BP06 are provided in Fig. 6. The results largely mirror those of the tongue blade region. For /a/, the nasal vowels displayed a higher AV compared to their oral congeners for nine speakers. The oral vowel displays a higher AV than the nasal vowels for three speakers. The nasalized vowel displays a higher AV compared to the oral vowel for seven speakers, and a lower AV for five speakers. For the nasal vowels, the word-final nasal vowel displays a higher AV compared to the word-medial nasal vowel for ten of twelve speakers.

For /i/, the nasal vowels display a higher AV compared to the oral vowel for ten speakers. Only two speakers display the opposite pattern. The nasalized vowel displays a higher AV compared to the oral vowel (and lower than that of the nasal vowel) for ten speakers, overlapping AV for one speaker, and a lower AV for one speaker. For the nasal vowels, the word-final nasal vowel displays a higher AV compared to the word-medial nasal vowel for nine of twelve speakers.

For /u/, the oral vowel displays a higher AV compared to the nasal vowels for ten speakers. Only two speakers display the opposite pattern. The nasalized vowel displays a lower AV compared to the oral vowel for seven speakers, overlapping AV for one speaker, and a lower AV for four speakers. For the nasal vowels, the word-final nasal vowel displays a lower AV compared to the word-medial nasal vowel for four of twelve speakers, and a higher AV for eight speakers.

In regards to the results for the phonetically nasalized vowels, two general patterns emerged—one in which the nasalized vowels showed articulatory similarities to the oral vowels, and one in which they showed similarities to the nasal vowels. The pattern that predominantly emerged differed for each vowel

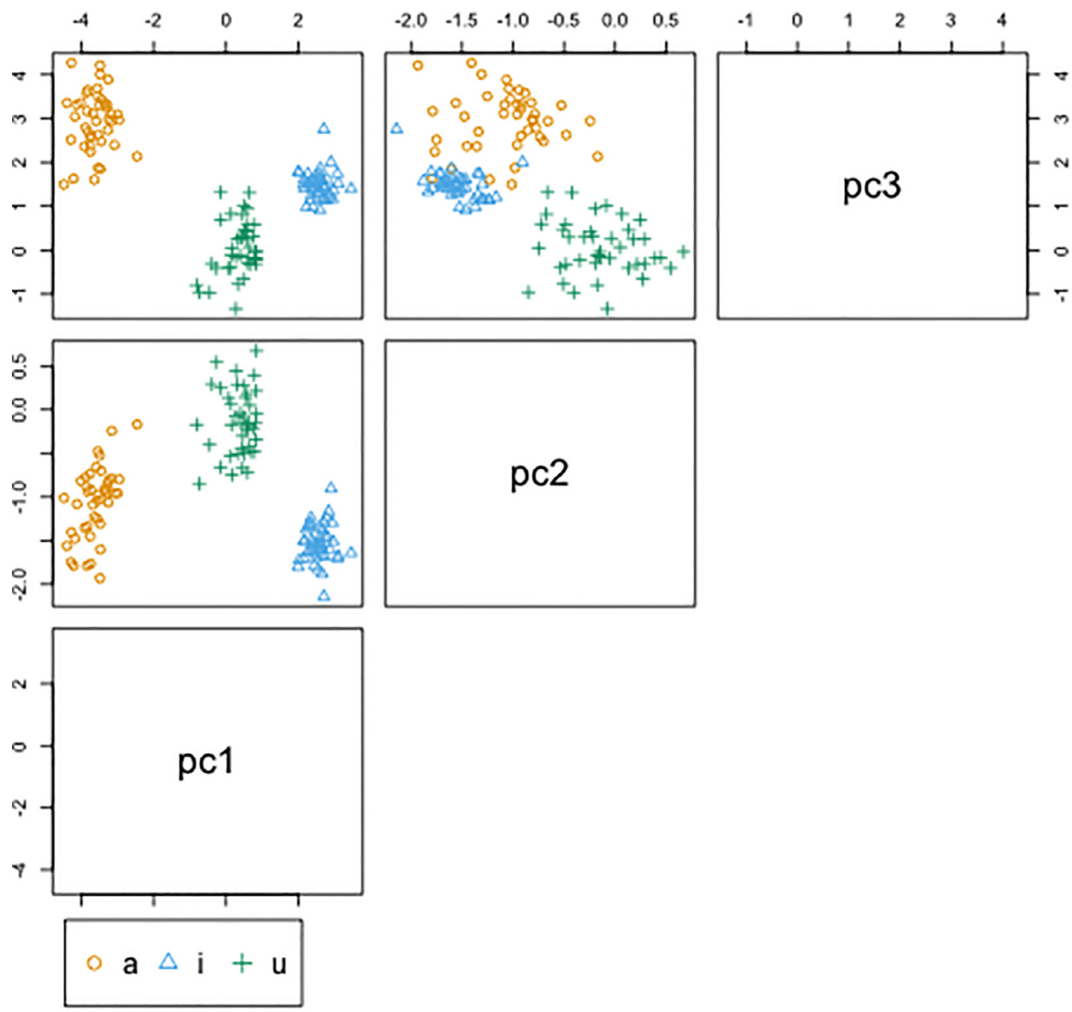


Fig. 4. Scores for PC1–3 for speaker BP06, by vowel quality.

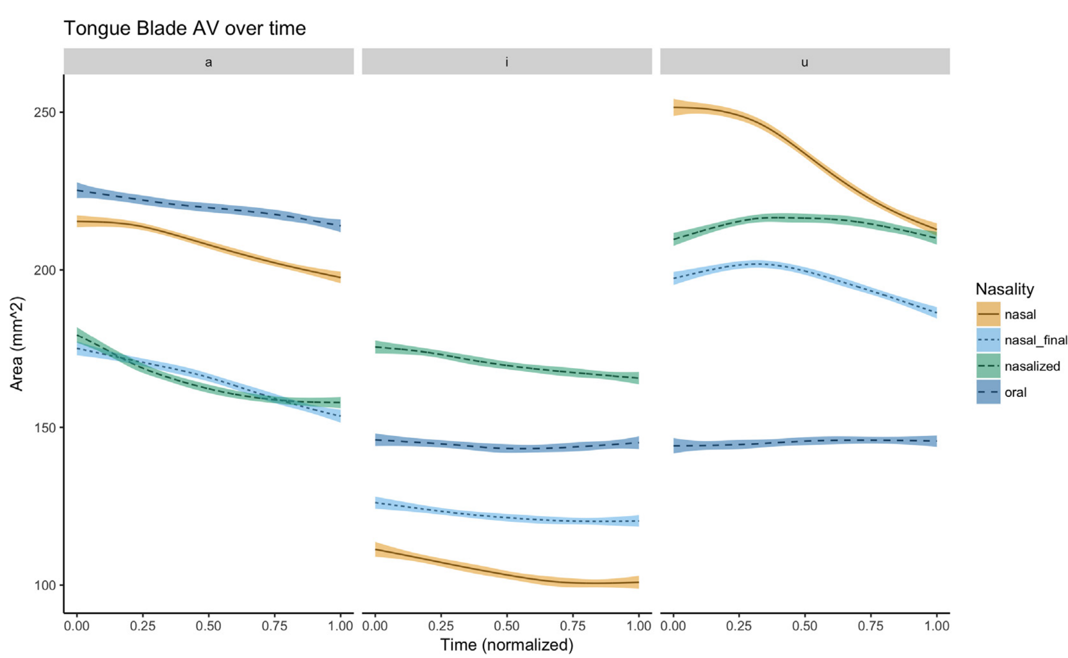


Fig. 5. AV for the tongue blade over time with 95% confidence intervals, by vowel, for speaker BP06.

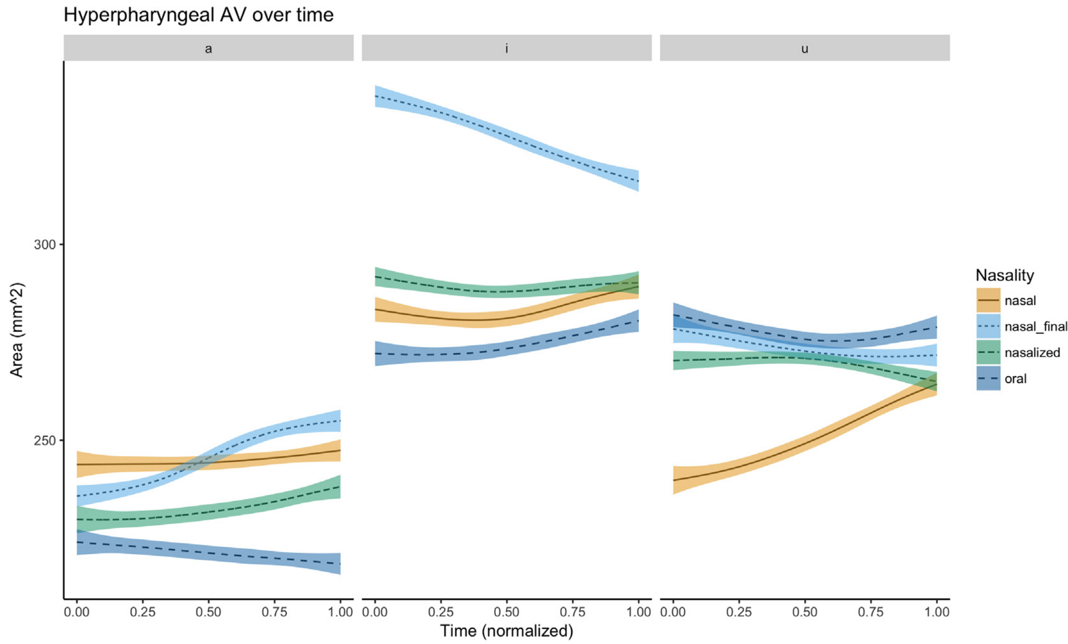


Fig. 6. AV for the hyperpharynx over time with 95% confidence intervals, by vowel, for speaker BP06..

category. For /u/, most speakers (nine of twelve) produce nasalized vowels in a manner similar to the nasal vowels. For /i/, the nasalized vowels tend to be more similar to the oral vowels, for ten of twelve speakers. Five of these speakers produce the nasalized vowels with higher AV compared to the oral vowels for the tongue blade region. These speakers do not show lower nasalized AV in the hyperpharyngeal region, compared to the oral vowels. The results for /a/ are mixed—four speakers produce nasalized vowels similarly to the oral vowels, while the remaining eight produce them more similarly to the nasal vowels.

PC2 accounted for an average of 17% of the total variance in the data (range 14–20%), and PC3 accounted for an average of 10% of the variance in the AF data for each speaker (range 7.8–14%). In no instances did PC2 and PC3 together account for more variance than PC1. The articulatory interpretation of PC2 was more varied than that of PC1. For five speakers, PC2 was associated with the hypopharyngeal region, defined as the bottom third of the pharynx. For five speakers, PC2 was associated with the tongue tip region. (There was one speaker for whom PC1 also correlated with the tongue tip region.) For eight speakers, the tongue dorsum/velar region was the articulatory interpretation of PC2. For one speaker, the labial region was the interpretation, and for one other speaker, the mediopharynx, defined as the middle third of the pharyngeal region, was the interpretation of PC2. (Note that for some speakers, PC2 has multiple interpretations, similar to PC1.) In no instances are PC2 and PC3 interpreted as adjacent spaces in the vocal tract. Results for PC2 are found in Table B.5.

3.3. Tongue shape

Results for tongue shape largely mirror the results for tongue blade and hyperpharyngeal AF. When AV is relatively high, tongue blade position is relatively low, and the tongue root is further retracted, indicating a more constricted pharynx. This confirms that the AV analysis reflects changes in oropharyngeal articulation, rather than velar lowering. Graphical results for tongue contours for speaker BP06 are provided in Fig. 7. A summary of the results for the tongue shape analysis is found in Table 2.

With regards to other articulators, the nasal vowels /ĩ/ and /ũ/ show overall tongue raising throughout their relative durations for all speakers, with narrow constrictions by the end of their durations. For /ĩ/, this is especially prominent in the tongue tip region, whereas for /ũ/, this is prominent in the tongue dorsum region.

3.4. Acoustic results

The GAM run on the F1 dataset accounted for 53% of the deviance in the data. Time, vowel, nasality condition, and gender (males showing overall lower F1 compared to females) were all significant effects on AF. Speaker also showed a significant effect on AF, indicating that individual differences were present in the data. Results of the GAM are summarized in Table 3. The s(X) notation is used to denote a smooth of a continuous predictor variable in the GAM. The intercept is interpreted similarly to that of a linear model with categorical predictors. Here, the intercept represents the nasal /ã/ for female speakers. EDF and reference degrees of freedom (in parentheses) are given for smooth terms in the model to show effects of time on categorical conditions.

Very predictable patterns of F1 are observed for the low vowel. F1 is much higher for the oral /a/, which is in line with previous studies on BP vowels (Shosted, 2015). This pattern holds for all speakers. This pattern holds with articulatory research showing nasal /ã/ as being produced with a raised tongue body compared to oral /a/. In comparing the nasal, word-final nasal, and nasalized /a/, the results show that nasal /ã/ generally is produced with the lowest F1. The nasalized

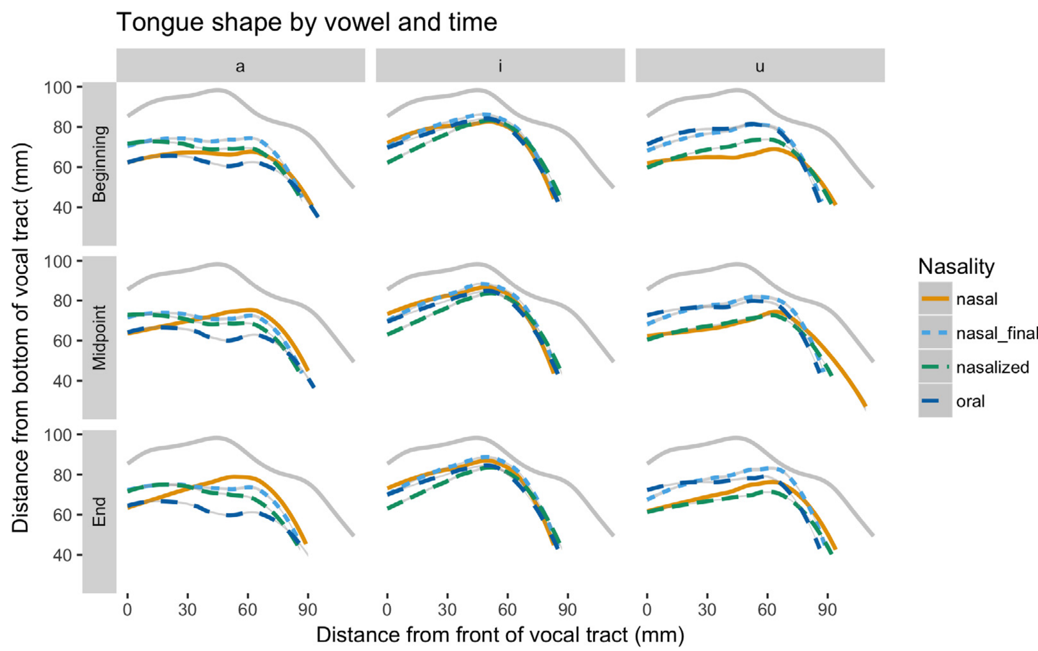


Fig. 7. Tongue shape by nasality and vowel at three different time points (BP02). Grey indicates the superior wall of the vocal tract, including the alveolar ridge and palate. The tongue shape is graphed using a GAM spline smooth, with 95% confidence intervals surrounding the spline.

Table 2
Results of tongue shape analysis, by height of tongue blade, at midpoint of vowel for all speakers. Dark shading and bold text indicates a higher tongue blade position for the nasal vowel compared to the oral vowel, and light shading and italic text indicates a higher tongue blade position for the oral vowel compared to the nasal vowel. Text indicates the nasality condition that the nasalized vowel is more similar to (though not identical to). For example, for speaker BP02, /ã/ displays a higher tongue blade than /a/, and the nasalized vowel's tongue blade position is closer to that of the nasal vowel than the oral vowel. /i/ displays a higher tongue blade position than /ĩ/, and the nasalized vowel's tongue blade position is closer to that of the oral vowel than the nasal vowel.

Speaker	/a/	/i/	/u/
BP02	**nasal**	*oral*	*oral*
BP04	**nasal**	*nasal*	*nasal*
BP05	**oral**	**nasal**	**nasal**
BP06	**nasal**	**oral**	nasal
BP09	**oral**	*nasal*	**nasal**
BP10	**nasal**	**oral**	*nasal*
BP14	**nasal**	**oral**	*nasal*
BP17	**oral**	**oral**	*nasal*
BP18	**nasal**	*oral*	*nasal*
BP19	**nasal**	*oral*	*oral*
BP20	**oral**	**oral**	*nasal*
BP21	**nasal**	*oral*	*nasal*

vowel's F1 is between that of the oral and nasal vowels, though it is closer to the nasal vowels' ranges.

For /i/, two patterns emerge. For most speakers, the nasal vowels show a higher F1 across time. This acoustic result is indicative of a lower tongue position, which is seen for these same speakers. For the second pattern, which is produced by four of the twelve speakers, the nasal vowels show a lower F1 value compared to the oral vowel. The nasalized /i/ patterns similarly to the oral vowel /i/.

For /u/, nasal vowels generally show a higher F1 than oral vowels. This acoustic result is indicative of a lower tongue position for the nasal vowels, compared to the oral vowels. For most speakers, the nasalized vowel patterns similar to the nasal vowels. Results for F1 for BP21 are seen in Fig. 8.

Table 3
Results of the GAM for F1 data, including the EDF and reference degrees of freedom (in parentheses) for smoothed model components.

	F1
(Intercept)	480.48 (32.53)***
Vowel (i)	−167.79 (0.80)***
Vowel (u)	−160.21 (0.80)***
Nasality (nasal_final)	−1.84 (0.92)*
Nasality (nasalized)	20.42 (0.93)***
Nasality (oral)	65.50 (0.92)***
EDF: s(Time)	4.84 (5.28)***
EDF: s(Time):Vowel (a)	7.45 (8.39)***
EDF: s(Time):Vowel (i)	1.00 (1.00)***
EDF: s(Time):Vowel (u)	0.00 (0.00)
EDF: s(Time):Nasality (nasal)	6.08 (7.20)***
EDF: s(Time):Nasality (nasal_final)	5.52 (6.62)***
EDF: s(Time):Nasality (nasalized)	0.00 (0.00)
EDF: s(Time):Nasality (oral)	6.71 (7.79)***
EDF: s(Speaker)	4.99 (11.00)***
EDF: s(Speaker,Time)	72.00 (107.00)***
EDF: s(Sex)	0.47 (1.00)***
EDF: s(Sex,Time)	5.46 (17.00)*
AIC	750345.52
BIC	751460.10
Log Likelihood	−375049.88
Deviance	440042840.78
Deviance explained	0.61
Dispersion	6858.58
R^2	0.61
GCV score	375262.96
Num. obs.	64280
Num. smooth terms	12

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

4. Discussion

Results of the GAM performed on AF data indicate a significant difference between nasality conditions and vowel quality across the data set. This model served as an initial indication that there is a difference in oropharyngeal articulation between

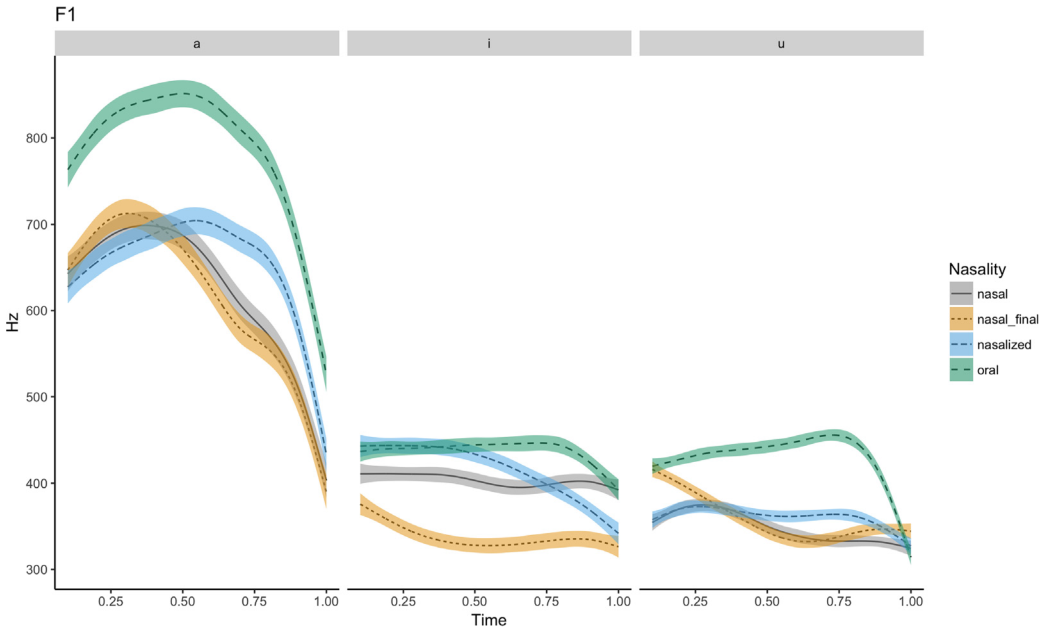


Fig. 8. F1 as a function of time, by vowel category.

nasal, oral, and nasalized vowels, across vowel qualities. The GAM results therefore are a foundation for the PCA-guided analysis, which served to highlight the regions of the vocal tract responsible for the differences between vowels and nasality conditions.

The most conclusive result of this study is the oropharyngeal distinction between the oral/nasal vowel congeners /a∼ã/. The nasal vowels displayed a much higher tongue blade position and a wider hyperpharyngeal region, compared to the oral vowel. This confirms descriptions of this vowel, frequently transcribed as a near-open central nasal vowel /ɐ̃/ (Barbosa & Albano, 2004; Shosted, 2015), but makes it clear that the distinction between these vowel congeners is a matter of oropharyngeal articulation, not merely velar lowering. This is potentially due to the nature of the vowel system of BP—/ã/ is the only central nasal vowel, which may allow for more variability in the height dimension. The nasalized /a/ shows articulatory patterns intermediate between the oral and nasal vowels, though for the majority of speakers, its configuration is slightly more similar to the nasal vowel. Because of the vast difference in oral configuration between the oral and nasal low vowels, there is more room for modulation of the oropharyngeal characteristics of the nasalized /a/, and it is possible that the higher tongue blade position for /ã/ exerts some influence on the production of the nasalized vowel.

Enhancement may be insufficient to entirely explain the large difference between the oral and nasal low vowels; early language contact between European and indigenous populations in Brazil may have played some role, as well. The structural influence of Tupi–Guarani languages on modern BP is controversial and complex (Rodrigues, 2014) and so we offer the following as a very tentative hypothesis. Tupinambá (Old Tupi) had a high central vowel (preserved as *langley*⟩ in texts) that could be phonemically nasal or oral (e.g., /ɨbɨ̃ja /*ybyȋâ* ‘interior part’ (Navarro, 2007)). It appears in many names of places, flora, and fauna. In 17th-century Brazil, many spoke a mixed Tupi/Portuguese language called Língua Geral of São Paulo; this language contained both Tupinambá and Portuguese lexical items. An exemplar-driven account might posit that Tupinambá words or syllables containing /ɨ̃/ or /ɨ/ were of sufficient frequency and recentness in the minds of Língua Geral speakers to influence their pronunciation of Portuguese lexical items containing the similar vowel /ã/, perhaps already raised somewhat to enhance its distinction from the oral low vowel.[4]

The frequent but not categorical modification of the nasalized low vowel to resemble the nasal low vowel, as demonstrated here, may be a good example of a sound change in progress. Perceptual studies are warranted to determine how differentiable they are.

For the oral/nasal vowel congeners /i∼ĩ/, modulations were made in the tongue blade and hyperpharyngeal regions, though these were not nearly as substantial as those made for the low vowel congeners. For most speakers, a slightly lower tongue blade position and a more constricted hyperpharyngeal region for /ĩ/ were observed, compared to /i/. For a minority of speakers, however, a slightly higher tongue blade position and a wider hyperpharyngeal region for /ĩ/ were observed, compared to /i/. The nasalized vowel tended to show articulatory patterns similar to those of the oral vowels. Those speakers that produce /ĩ/ with a slightly higher tongue blade position and a wider hyperpharyngeal region compared to /i/, also show lower tongue blade positions for the nasalized /i/ compared to the oral vowel. This suggests a compensatory articulation to counteract the acoustic effects of nasal coupling.

The nasal vowels display a lower tongue blade position and a narrower hyperpharynx for /ũ/ compared to /u/. The nasalized

[4] One example of the confusion between Tupinambá /ɨ/ and its nasal/nasalized reflex in modern BP is the name of the Tapanhuna River of São Paulo, which comes from Tupinambá/tapɨʔɨjuna/ (Navarro, 2007, p. 600). The second low vowel of *Tapanhuna*, arguably nasal or nasalized, depending on the syllabification, comes from the etymological high central vowel of Old Tupi.

vowel tended to show articulatory patterns similar to those of nasal vowels for /u/. The result for /u/ is likely due to spatial limitations in the oral cavity—velum lowering results in a "crowded" posterior region of the oral cavity, which may push the tongue blade forward to avoid epiphenomenal contact with the velum. This causes the tongue to move closer to the region where the nasal /ũ/ is positioned, though rarely does it fully reach the target region of the nasal vowel. (On the contrary, for the front vowel /i/, there is more room for the tongue to maintain its position, even with the effects of coarticulatory nasalization.)

The relatively smaller movement of the tongue for /ĩ/ and /ũ/, compared to /ã/, is arguably because of vowel category maintenance. BP also has the nasal vowels /õ/ and /ẽ/ in its vowel inventory. If the high nasal vowels displayed higher magnitudes of articulatory differences from their oral congeners, they could potentially be conflated with the mid nasal vowels. In this case, maximizing the difference between /i∼ĩ/ and /u∼ũ/ through enhancement would result in a minimization of the differences between /ĩ∼ẽ/ and /ũ∼õ/, and could create a potential for phonemic merger. If a maximal number of contrasts is to be held constant within a language, as per Dispersion Theory (Flemming, 2004, p. 236), the /ĩ∼ẽ/ and /ũ∼õ/ distinctions should be maintained. Further work is needed to study how the mid nasal vowels are produced, and how this production results in a stable distinction between five nasal vowels.

The results presented here are similar to those in Shosted (2015), who observed lingual raising for the nasal vowels /ĩ ũ ã/ in comparison with their oral congeners, and with da Matta Machado (1993), who found a relative reduction in oral cavity volume for nasal vowels.

Based on the results of this study, we argue that oral and nasal vowels maintain their own motor plans. That is, the acoustic goals in regards to production of the vowel congeners manifest in different oropharyngeal articulatory configurations, in addition to oral/nasal coupling. We argue that this difference in the phonetic surface form may mirror the phonological distinction that has been posited between oral/nasal vowel congeners. Specifically, we argue that the nasal vowels analyzed in this study are underlyingly $/\tilde{V}/$ in nature, rather than /VN/.

Data regarding the nasalized vowels, which are inherently /VN/ sequences, gives further evidence towards this argument. Nasalized /i/ shows articulatory configurations quite similar to oral vowels. Furthermore, for a minority of speakers, the nasalized vowel actually manifests articulatory configurations that would result in acoustic effects opposite of the nasal vowels. This is arguably a compensatory articulation strategy to maintain the nasal vowels within the phonemic category of oral vowels. Therefore, in addition to articulatory distinctions between oral and nasal /i∼ĩ/, there is significant articulatory difference between the nasal and nasalized vowels.

Nasalized /a/ shows an articulatory configuration intermediate to that of the nasal and oral vowels. While many speakers show articulatory configurations slightly closer to that of the nasal vowels, there is still considerable distance in the position of articulators between the nasal and nasalized vowels. Similarly, the nasalized /u/ shows an articulatory pattern similar to that of the nasal vowels, presumably due to spatial constraints in the posterior region of the oral cavity. However, while it is more similar to the nasal vowels, the nasalized vowel crucially does not show overlapping configurations with the nasal vowels (for example, see Fig. 5). Furthermore, GAM results show significant differences in AF for nasal and nasalized vowels, indicating a difference in vocal tract aperture. The differences between nasal and nasalized vowels are therefore further evidence that nasal vowels are not /VN/ in nature.

This study highlights the importance of lingual and pharyngeal variation in the articulation of oral and nasal vowels, across all vowel categories studied. We provide further evidence that nasalization is associated with oropharyngeal effects in addition to velar lowering. The region of the vocal tract corresponding to the tongue dorsum and velum showed relatively lower importance in the PCA analysis—the region was analyzed as a correlate of PC2 for eight speakers, and PC3 for four speakers. The lower amount of variability in the velar region compared to lingual regions suggests that speakers maximally use the muscular flexibility of the anterior portion of the tongue to their advantage in production of complex sounds, such as nasal vowels. This finding is similar to analyses of French, which likewise demonstrate articulatory distinctions between oral/nasal vowel congeners.

It is important to note that the lingual and pharyngeal manipulation of the vocal tract implies specific changes in the acoustic output. Constrictions in the hyperpharyngeal region typically manifest in F1 raising, while constrictions in the anterior region of the vocal tract result in F1 lowering. These articulatory effects can serve to enhance the effects of oral/nasal coupling, and thus the perceptual prominence of nasalization of these vowels. Specifically, F1 of /ũ/ is expected to be higher than that of /u/ due to nasal coupling. Increased constriction in the hyperpharynx and lower tongue position both raise F1. Acoustic results show that F1 of nasal vowels is higher than that of oral vowels for /u/, as expected. F1 of /ã/ is expected to be lower than that of /a/, also due to nasal coupling. Expansion in the hyperpharynx and higher tongue blade position both lower F1. Acoustic results show robust differences between the oral and nasal vowels, with the nasal vowels maintaining a much lower F1 compared to oral vowels. F1 of /ĩ/ is expected to be higher than that of /i/ because of oral/nasal coupling. The results for /i/ show much more individual variation. Some speakers show evidence of hyperpharyngeal expansion and tongue body raising, which would further modulate F1 though in the opposite direction than what is expected for acoustic enhancement of nasalization. We argue that this modulation is to maintain maximal distinction between the mid and high nasal vowels /ĩ/ and /ẽ/.

Results indicate that /ĩ/ and /ũ/ show nasal coda consonant emergence. This is evident in the tongue shape results, which show raising of the tongue tip towards the palate for /ĩ/ and raising of the tongue dorsum towards the velum for /u/. It is important to note that this is not coarticulation with the following consonant, which is alveolar. While there is evidence of constriction in these regions, the degree of constriction is variable across speakers, indicating that this is a potential sound change in progress, and has not reached phonemic status. Further work regarding the production and perception of nasal vowels is needed to determine the status of the progression of this sound change in BP.

The emergence of these coda consonants can further contribute to the phonemic distinction of oral and nasal vowel congeners. While this would result in a biphonemic understanding of phonemic nasal vowels in BP, the nasal vowel maintains its own underlying phonemic status. That is, we argue that the underlying form of these vowels is /Ṽ/ rather than /VN/ due to different oropharyngeal states, though the form [ṼN] is emerging in some productions of these vowels. Nasal coda emergence is argued to be an emerging strategy to maximize the distinction for nasal and oral vowel congeners, especially /i∼ĩ/. This is an alternative strategy to vowel quality enhancements of the acoustic effects of nasalization, as the results of those effects possibly minimize differences between /ĩ∼ẽ/ and /ũ∼õ/.

The absence of coda consonant emergence for the contextually nasalized vowel arguably maintains category stability within the [−NASAL] group, despite oropharyngeal distinctions between oral and nasalized vowels. It is important to note that these nasal coda consonants are emerging for nasal high vowels, but not for the nasal low vowel. (This observation is also reported in Shosted (2006) and Barlaz, Fu, and Shosted, et al. (2015b), where nasal coda emergence for the nasal mid vowels /õ/ and /ẽ/ is observed, as well.) The inherent open quality of the vowel restricts the ability of a narrow constriction to be made for a coda consonant. Therefore, differences in oropharyngeal articulation are especially important for enhancing the distinction between the low oral/nasal vowel congeners.

The difference in articulation of nasal and phonetically nasalized vowels is further evidence that nasal vowels in BP have achieved phonemic status, as they do not follow the same articulatory patterns as nasalized vowels, which are inherently /VN/ sequences. While nasalized /a/ and /u/ show patterns similar to those of the nasal vowels in their tongue blade and hyperpharyngeal positions, they are not totally merged in their configuration (based on the results of the SSANOVA plots and the GAM). When comparing [±NASAL] segments to determine phonological contrast, the entire articulatory profile across time must be taken into account. Following the description of phonological nasalization as a durational target in Cohn (1990), the feature [+NASAL] must include time-dynamic oropharyngeal articulation, as well as oral/nasal coupling.

It is important to note that the vowels being analyzed are given word- and phrase-level prominence in their production. Following Cho, Kim, and Kim (2017), we argue that the phonetic manifestations of BP phonemic vowels are paradigmatic enhancements of the underlying nasality of these sounds. In regards to the nasalized vowels, we do not see evidence of enhancement of nasality in the same manner as for the nasal vowels. In fact, in some cases the observed differences in articulation would result in attenuation of the acoustic effects of nasality. This can be argued to enhance the underlying orality of these vowels, in a similar manner to American English (Cho et al., 2017). This gives further cross-linguistic evidence towards the localized hyperarticulation hypothesis (de Jong, 1995; de Jong, 2004), which is important for understanding the relationship between phonemic articulation and prosodic structure. Further research is necessary to compare the articulation of BP nasal and nasalized vowels in various prosodic contexts and with different levels of word-level stress, insofar as phonological constraints allow.

5. Conclusion

The findings from this study show the importance of oropharyngeal articulations in the distinction of oral and nasal vowels, and provide direct articulatory evidence that nasal and oral vowels are phonemically distinct in BP, due to what appear to be distinct motor plans. Specifically, /ã/ showed a higher tongue blade and less constricted pharynx compared to /a/, /ũ/ showed a lower tongue blade and more constricted pharynx compared to /u/, and /ĩ/ showed a slightly higher tongue blade and less constricted pharynx compared to /i/. Thus, we argue that BP nasal vowels are underlyingly /Ṽ/ in nature. The robust articulatory differences between the low oral/nasal vowel congeners provides further evidence that the two vowels have very different motor plans, and the latter should be transcribed as /ɐ̃/. Furthermore, many of the articulatory effects are predicted to enhance the effects of nasalization on the acoustic output. The comparison of nasal and nasalized vowels shows that there is variability in the descriptor "nasal," and that certain articulatory strategies are available to speakers in order to distinguish [+NASAL] phonemes from [−NASAL] (i.e., oral and nasalized) phonemes. These strategies are used in different ways for different vowel categories, and while there is some individual variation, within-category oropharyngeal variations are fairly systematic. Within the feature specification [–NASAL], considerable articulatory variation is tolerated. These findings were possible because of recently-developed techniques in rt-MRI data acquisition and analysis that allow researchers to observe and resolve the movements of articulators with the necessary spatiotemporal resolution. Future work will apply these imaging techniques to a direct study of nasopharyngeal aperture in nasal and nasalized vowels, to determine potential differences in velar timing. The results of this study further exemplify the complexities of the articulatory inversion problem (Maeda, 1993) and chart a way forward to deal with it using high-dimensional imaging data. Our findings lend further evidence to the notion that the goal of speech communication is acoustic in nature (Ohala, 1996), as multiple articulatory cues are being integrated into a signal to produce a distinct phonological unit.

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Appendix A. Word list

Table A.4
List of words used in production experiments.. The three penultimate columns are the frequencies in the corpora: ASPA (Cristófaro-Silva et al., 2005), São Carlos (Linguateca, 2016), and Corpus do Português (Davies, 2016).

Vowel	Word	IPA	Gloss	ASPA	São Carlos	Corpus do Português	Vowel Type
/u/	tributo	[tɾiˈb**u**tu]	tax	3550	322	78	oral
	tribuna	[tɾˈib**u**na]	tribune	1360	1296	80	nasalized
	abunda	[aˈbũda]	abounds	61	26	10	nasal
	bebum	[bɛˈbũ]	bum	24	2	2	nasal
/a/	babado	[baˈb**a**du]	frill	392	43	8	oral
	propano	[pɾoˈp**a**nu]	propane	32	4	11	nasalized
	tapando	[taˈpãdu]	cover	132	24	13	nasal
	tupã	[tuˈpã]	Tupi god	429	26	3	nasal
/i/	cabido	[kaˈb**i**du]	fit	25	4	3	oral
	cabine	[kaˈb**i**ni]	cabin	2355	234	50	nasalized
	subindo	[suˈbĩdu]	go up	2499	388	199	nasal
	cupim	[kuˈpĩ]	termite	237	31	23	nasal

Appendix B. Summary of results

A summary of the results for AV for PC1-2 are shown in Table B.5.

Table B.5
Summary of the results of the PCA-based articulatory analysis for the vowels /a/, /i/, and /u/. Dark shading and bold text indicates higher AV for the oral vowel compared to the nasal vowel. Light shading and italic text indicates higher AV for the nasal vowel compared to the oral vowel. Text indicates the nasality condition that the nasalized vowel is more similar to (though not identical to). For example, for speaker BP02, /a/ displays a wider opening in the tongue blade region than /ã/, and the nasalized vowel's tongue blade area is closer to that of the nasal vowel than the oral vowel. /i/ displays a wider opening in the tongue blade region than /ĩ/, and the nasalized vowel's tongue blade area is closer to that of the oral vowel than the nasal vowel.

Speaker	PC	Articulatory Interpretation	AV/a/	AV/i/	AV/u/
BP02	PC1	tongue blade	**nasal**	*oral*	*oral*
BP02		hyperpharynx	*nasal*	*nasal*	**nasal**
BP02	PC2	hypopharynx	*nasal*	*oral*	*oral*
BP02		lips	**nasal**	**oral**	*oral*
BP04	PC1	hyperpharynx	*oral*	*oral*	**oral**
BP04	PC2	hypopharynx	*oral*	**oral**	**oral**
BP04		tongue tip	*oral*	**nasal**	**nasal**
BP05	PC1	hyperpharynx	**nasal**	**nasal**	**nasal**
BP05		tongue blade	**oral**	**nasal**	**nasal**
BP05	PC2	hypopharynx	*nasal*	*oral*	**nasal**
BP05		tongue dorsum/velum	**nasal**	**nasal**	**nasal**
BP06	PC1	tongue blade	**nasal**	**oral**	*nasal*
BP06		hyperpharynx	*oral*	*nasal*	**nasal**
BP06	PC2	hypopharynx	**nasal**	*nasal*	*oral*
BP06		tongue tip	**nasal**	**nasal**	*oral*
BP09	PC1	tongue blade	**oral**	*nasal*	**nasal**
BP09		tongue tip	**nasal**	**oral**	**nasal**
BP09		hyperpharynx	**nasal**	**nasal**	*nasal*
BP09	PC2	tongue dorsum/velum	**nasal**	*nasal*	*nasal*
BP10	PC1	tongue blade	**nasal**	**oral**	nasal
BP10		hyperpharynx	*nasal*	*nasal*	**nasal**
BP10	PC2	tongue dorsum/velum	**nasal**	**nasal**	**nasal**
BP14	PC1	tongue blade	**nasal**	**oral**	*nasal*
BP14		hyperpharynx	*nasal*	*nasal*	**oral**
BP14	PC2	tongue dorsum/velum	**nasal**	*nasal*	**nasal**
BP14		hypopharynx	*nasal*	*oral*	*nasal*
BP17	PC1	tongue blade	**oral**	**oral**	*nasal*
BP17		hyperpharynx	*nasal*	*oral*	**nasal**
BP17	PC2	tongue dorsum/velum	**nasal**	**nasal**	**nasal**
BP18	PC1	tongue blade	**nasal**	*oral*	*nasal*
BP18		hyperpharynx	*oral*	*nasal*	**oral**
BP18	PC2	tongue dorsum/velum	**nasal**	**nasal**	**nasal**
BP18		tongue tip	*oral*	*nasal*	**nasal**

(*continued on next page*)

Table B.5 (*continued*)

Speaker	PC	Articulatory Interpretation	AV/a/	AV/i/	AV/u/
BP19	PC1	tongue blade	**nasal**	*oral*	*oral*
BP19		hyperpharynx	*oral*	*nasal*	**nasal**
BP19	PC2	mediopharynx	*oral*	*nasal*	*nasal*
BP19		tongue tip	**nasal**	**oral**	*nasal*
BP20	PC1	tongue blade	**oral**	**oral**	*nasal*
BP20	PC2	hyperpharynx	*nasal*	*nasal*	**nasal**
BP20		tongue dorsum/velum	**nasal**	**oral**	**nasal**
BP21	PC1	tongue blade	**oral**	*oral*	*nasal*
BP21		hyperpharynx	**nasal**	*nasal*	*nasal*
BP21	PC2	tongue dorsum/velum	**nasal**	*nasal*	**nasal**
BP21		tongue tip	**nasal**	**oral**	*nasal*

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